The JuMBO Puzzle and Potential Reconciliations of Theory and Observation

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1 INTRODUCTION

The James Webb Space Telescope (JWST) is the most recent space observatory produced by NASA in partnership with the ESA and the CSA. Launched at the end of 2021, its primary goal was to observe the very edges of our observable universe in order to study objects in existence just after the Big Bang.

JWST has already enhanced our understanding of the early universe (Curti et al. (2022); Rhoads et al. (2023)), revealed new features of Jupiter's atmosphere (Hueso et al. (2023)), and studied the inner Orion nebula (McCaughrean & Pearson (2023)). It was also in Orion nebula where JWST found hundreds of Jupiter-mass objects (some having mass as low as 60% of Jupiter's) floating freely in space. Peculiarly, 9% of these objects were observed in binary pairs. Current models of star formation do not permit the formation of objects below 3 Jupiter masses via gravitational collapse (Boyd & Whitworth (2005); Forgan & Rice (2011)). For a free-floating object to exist, it must either form through gravitational collapse, or be ejected from orbit around another object. Thus, planet ejection may explain many of these objects, but the existence of binary pairs indicates that these objects must either form together or be ejected together. Neither possibility has been predicted.

This essay will give a brief description of the gravitational collapse mechanism that forms stars and lower-mass objects, hopefully conveying the puzzling nature of these Jupiter-Mass Binary Objects (JuMBOs), before moving onto discuss two promising theories for their formation. The content of this essay has been tailored to a 2nd year astronomer, so a foundational knowledge of astrophysics is assumed.

2 GMC FRAGMENTATION AND THE IMPOSSIBILITY OF JUMBOS

Giant Molecular Clouds (GMCs) are the birthplace of stars. They are typically $\sim$ 30 parsecs across and can contain anywhere from a few $M_\odot$ to $\sim$ 10 million $M_\odot$ of Hydrogen (Miville-Deschênes et al. (2017)). Their density is far from uniform and varies from region to region in an environment dominated by turbulence. Regions of the cloud which are dense enough to collapse in on themselves are called *prestellar cores*. When a cloud will not dissipate, it is said to be *gravitationally bound*. In order for a bound core to collapse, its inward gravitational pull must overcome the outward pressure arising from the randomly distributed kinetic energy of its particles.

This is only the case when the core's mass is greater than a critical value called the *Jeans mass* which depends on the sound speed in the cloud and its density via the relation:

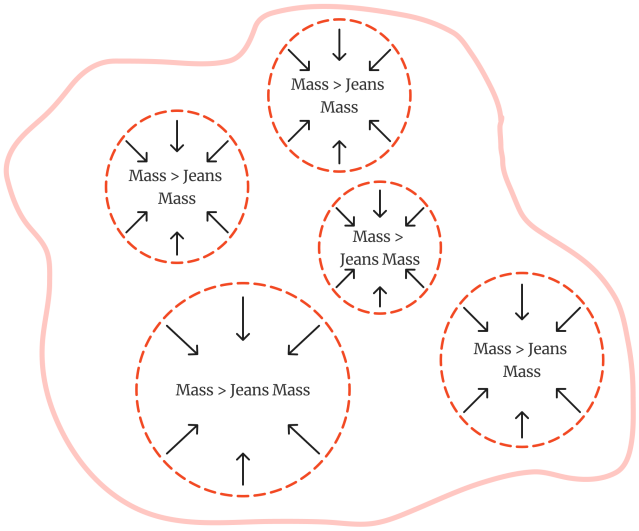

Figure 1. A very simple visualisation of 5 regions within one GMC core, all of which exceed the Jeans mass and have begun to collapse, causing the core to split into 5 fragments.

$$M_J \propto \frac{C_s^3}{\rho^{\frac{1}{2}}} \tag{1}$$

where M_J is the Jeans mass, C_s is the sound speed and ρ is the density of the cloud. Rees (1976)

Initially, the collapse is a slow process that occurs without altering the temperature of the core (because the gas is able to radiate away the energy gained from falling towards the centre of gravity). The sound speed is unaltered but the density increases, so during this phase of the collapse the Jeans mass **decreases**. This means the mass required for a region to collapse gets lower and lower. This may lead to fragmentation of the core when there are several Jeans mass-exceeding regions within it, as shown in Figure 1.

There is a second phase of core collapse which begins when the cloud becomes so dense that the gas cannot effectively radiate away its excess energy. At this point, no heat can be transferred from the core to its surroundings which allows the sound speed to increase. This dominates the impact of increasing density resulting in an **increasing** Jeans mass. Therefore there must be a minimum value of M_J, below which gravitational collapse cannot occur, implying no objects can form this way with a mass below this minimum. Early studies (Rees (1976); Low & Lynden-Bell (1976); Silk (1977)) placed the minimum Jeans mass at around 7 to 10M_{Jup}, while more recent

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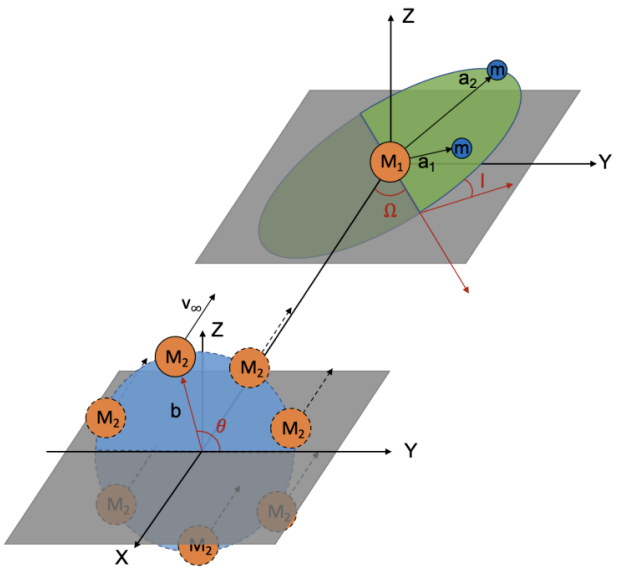

Figure 2. Diagram showing how the orientation of the orbital plane (top) may vary with respect to the motion of the interloping star (bottom). Wang et al. (2023)

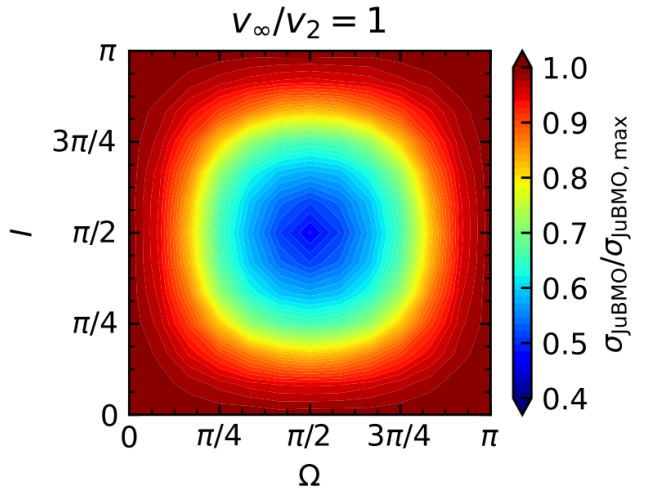

Figure 3. Data from Wang et al. (2023) showing how the probability of binary ejection varies with alignment with the orbital plane. Angles of I and Ω equal to $\pi/2$ correspond to a face-on interaction and result in a lower probability (indicted by the blue region) than in the edge-on interactions. I and Ω are displayed in Figure 2.

studies (Boyd & Whitworth (2005); Forgan & Rice (2011)) have provided a lower value of approximately $3M_{Jup}$.
So free-floating planetary-mass objects formed by this mechanism are not predicted. Though it's possible for planets to be ejected from their orbits, there is no known mechanism that can predict the existence of a significant fraction of these objects in binaries.
This leads us onto the two potential mechanisms to be discussed in this essay that might explain how these objects form at such low masses: *binary-planet ejection* and *photo-erosion*.

3 THE EJECTION HYPOTHESIS

A very recent (and not yet peer-reviewed) paper, Wang et al. (2023), claims to have simulated the ejection of pairs of planets due to gravitational interactions with a passing star. These types of interactions are thought to be common in regions of dense star formation (such as the inner Orion Nebula where JuMBOs were observed). Figure 2, shows the approach of an interloping star that will pass a planetary system causing ejections.

The study found that the probability of ejection depends on two key factors: the velocity of the interloping star, and the degree of alignment of the planetary system with the motion of that interloper. This is a fairly intuitive observation as a star approaching the system with motion that is **edge-on** (parallel to orbital plane), will interact with the planets for a greater amount of time than an interloper that approaches **face-on** (perpendicular to orbital plane). Furthermore, if this is happening with a high velocity, then more momentum will be imparted onto the planet, making ejection more probable. The data in Figure 3 displays this.

These ejections can only form binaries when both planets are ejected consecutively. This is actually **less** likely to occur with fast interlopers since they have less time to interact with the planets. The faster the interloper, the more likely it is to eject **one** planet, but the less likely it is to eject **a pair** of planets. Figure 4 shows that the fraction of binaries produced (with respect to free-floating

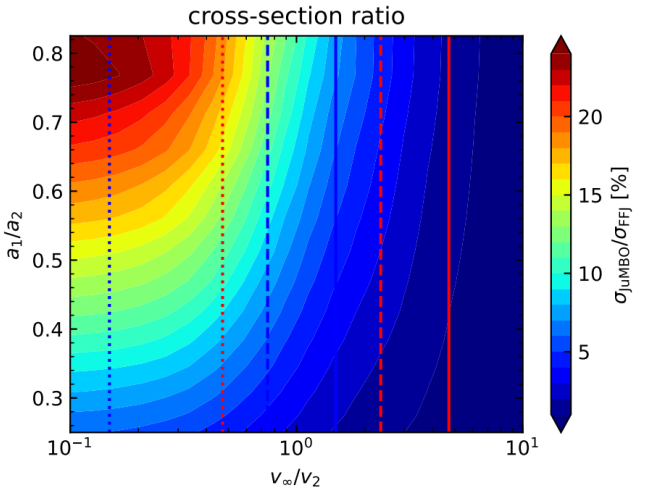

Figure 4. The ratio of JuMBO production to free-floating Jupiter production is shown to increase as the interloper velocity becomes slower and the distance between the two planetary orbits decreases. The maximum value shown by the red region is indicated to be roughly 20%. Wang et al. (2023)

objects) increases up to 20% with slow interlopers and closer orbital separation of the planets.

This maximum value of 20% is reasonably consistent with the ratio observed of 9% by JWST.
There is however a significant problem with this idea. Planets in orbit around a star are rarely closely aligned. The fraction calculated by these simulations hinges on the close alignment of the planets being approached by a passing star. This would imply an over-estimation of the true proportion of binaries formed via this method. Perhaps this over-estimation is so significant that this mechanism (or at least this mechanism alone) cannot explain the observed ratio.
A 2014 study showed that planets are able to form binary pairs while

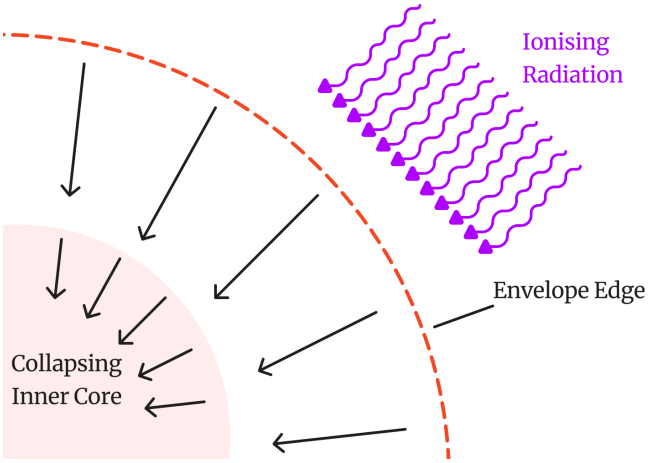

Figure 5. Diagram showing a prestellar core collapsing in on itself due to Lyman radiation ionising its outer edge.

remaining in orbit around a star, Ochiai et al. (2014), which may help to justify the requirement that the two planets are closely aligned at the time of interaction with a passing star. This was however found to be an uncommon occurrence and so is unlikely to happen often enough to make closely aligned planets as common an occurrence as is assumed in Wang et al. (2023).

4 PHOTO-EROSION OF PRESTELLAR CORES

It has been proposed (Whitworth & Zinnecker (2004)) that very low mass brown dwarfs can be formed from a prestellar core (that would otherwise go on to form a low or intermediate mass star) if its envelope (the surrounding material) is destroyed before it can be fully accreted. This happens through a process called *photo-erosion*. Photo-erosion occurs when a nearby massive star begins emitting Lyman radiation – light that ionises Hydrogen. The ionisation of the material at the edge of the envelope dramatically increases the external pressure on the inner envelope, which triggers a compression wave that propagates inwards, initiating the collapse of the core. This process is shown in Figure 5.

The ionised gas travels outwards and undergoes recombination, enabling it to absorb more ionising radiation Kahn (1969). This goes some way towards shielding the inner core from the Lyman photons but enough can still pass through the envelope's edge. An ionisation front travels through the core as it collapses. This continues until the core reaches a critical density where its gravity is so strong that ionised material can no longer escape, at which point the mass of the core is finalised.

We are therefore presented with a 'race' between the collapsing core and the ionising front, the result of which determines the mass of the final object formed through this mechanism. In a scenario where the core is slow to reach its critical density, the result will be a lower mass object than in the inverse scenario.

The study found that the final mass is dependent on three factors. There is a very strong dependence on the sound speed within the gas in the core, and weak dependencies on the rate of emission of Lyman photons and the density of Hydrogen in the envelope. Typical limits for these three factors were given by the paper. The most extreme values of which produce a minimum mass for objects formed this way of approximately 0.2 Jupiter masses. So it is plausible that Jupiter-mass objects could form via this mechanism.

However, the formation of JuMBOs via photo-erosion of prestellar cores relies on the satisfaction of two conditions. Firstly, the extreme limits mentioned above must occur enough for the frequent production of Jupiter-mass objects. Secondly, a significant fraction of the prestellar cores that are eroded must exist as stable bound pairs before **and** after undergoing photoerosion and collapse (which would upset the dynamics of the system) in order to produce these objects in binaries.

It remains unclear if these conditions are commonly met with in reality. Thus the likelihood of this mechanism to produce the number of JuMBOs observed by JWST is also unclear.

5 CONCLUSION

In conclusion, the discovery of Jupiter Mass Binary Objects (JuMBOs) by the James Webb Space Telescope (JWST) has raised questions about the formation of planetary-mass objects in the cosmos. These findings challenge our current understanding of star formation and the formation of binary systems. Traditionally, our knowledge of star formation suggests that objects below a certain mass cannot form via gravitational collapse. This mechanism does not allow for the existence of Jupiter-mass objects, let alone the occurrence of binary pairs among them.

This essay discussed two potential theories that may solve this. First, the ejection of planetary pairs due to gravitational interactions with passing stars offers a plausible explanation. However, the requirement of closely aligned planets at the time of interaction hinders the validity of this theory.

The second theory involves photo-erosion, where massive stars emit Lyman radiation, destroying the envelopes of prestellar cores while simultaneously triggering their collapse. This process may lead to the formation of Jupiter-mass objects, possibly in binary pairs. It is unclear whether the extreme conditions required for this mechanism occur frequently. Additionally, the likelihood of prestellar cores existing as gravitationally bound pairs both before and after undergoing photo-erosion remains uncertain.

Further research is needed to marry our understanding of star formation with the observation of JuMBOs. If JWST is able to find more JuMBOs elsewhere in space, differences or similarities with this first group could aid us in constraining their formation.

REFERENCES

Boyd D., Whitworth A. P., 2005, AA, 430, 1059
Curti M., et al., 2022, Monthly Notices of the Royal Astronomical Society, 518, 425
Forgan D., Rice K., 2011, MNRAS, 417, 1928
Hueso R., et al., 2023, Nature Astronomy, pp 1–9
Kahn F., 1969, Physica, 41, 172
Low C., Lynden-Bell D., 1976, MNRAS, 176, 367
McCaughrean M. J., Pearson S. G., 2023, A JWST survey of the Trapezium Cluster inner Orion Nebula. I. Observations overview (arXiv:2310.03552)
Miville-Deschênes M.-A., Murray N., Lee E. J., 2017, The Astrophysical Journal, 834, 57
Ochiai H., Nagasawa M., Ida S., 2014, ApJ, 790, 92
Rees M., 1976, MNRAS, 176, 483
Rhoads J. E., et al., 2023, The Astrophysical Journal Letters, 942, L14
Silk J., 1977, ApJ, 214, 152
Wang Y., Perna R., Zhu Z., 2023, arXiv preprint arXiv:2310.06016
Whitworth A. P., Zinnecker H., 2004, AA, 427, 299

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